

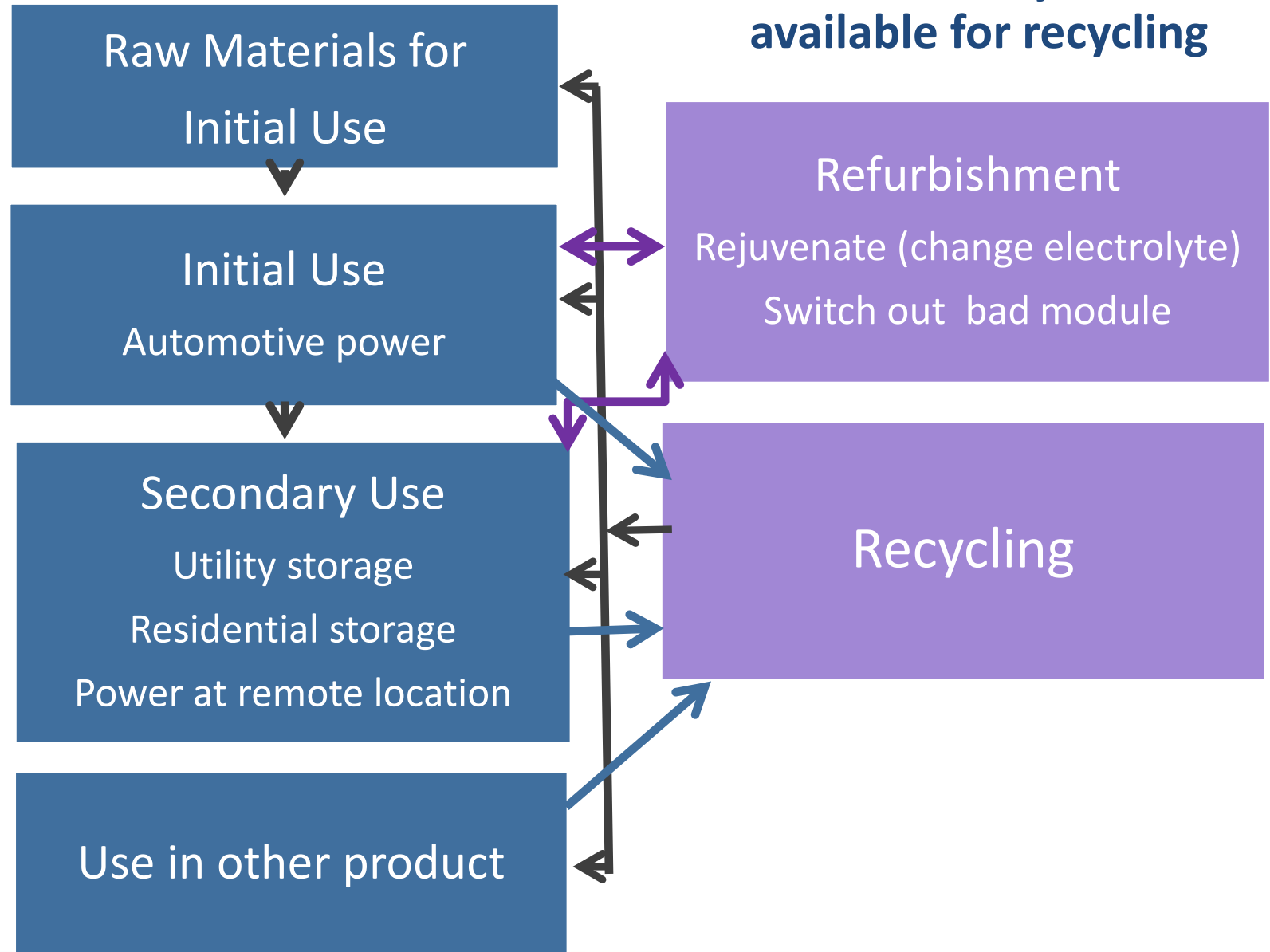
# Recycling of Lithium-Ion Batteries

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# Battery materials could get used multiple times... but eventually will be available for recycling

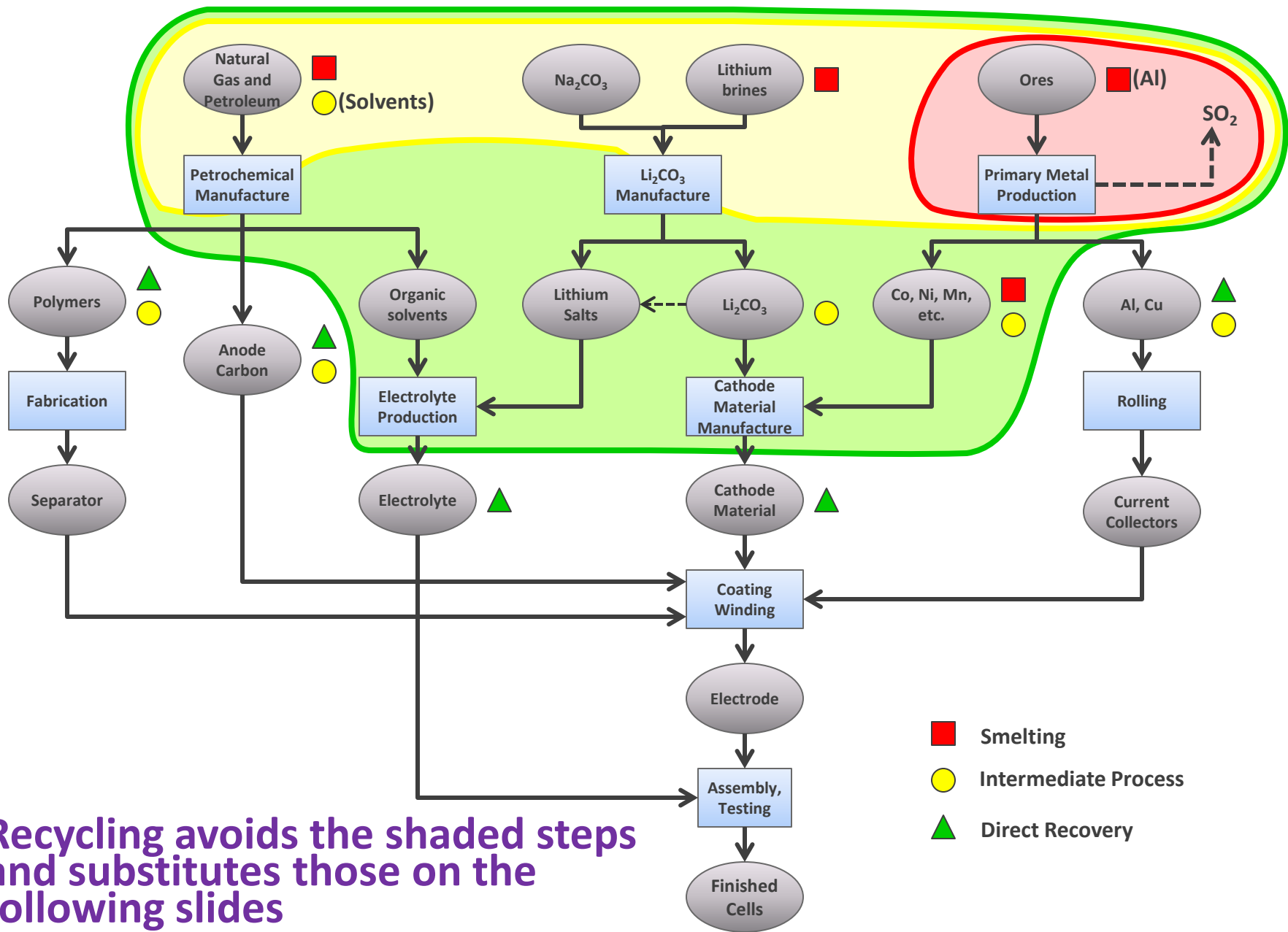


# All Li-ion recycling processes are NOT created equal!

- Different feedstock requirements
- Different products
- Different economics
- Different impacts

Four score and seven years ago our fathers brought forth on this continent, a new nation, conceived in Liberty, and dedicated to the proposition that all men are created equal.



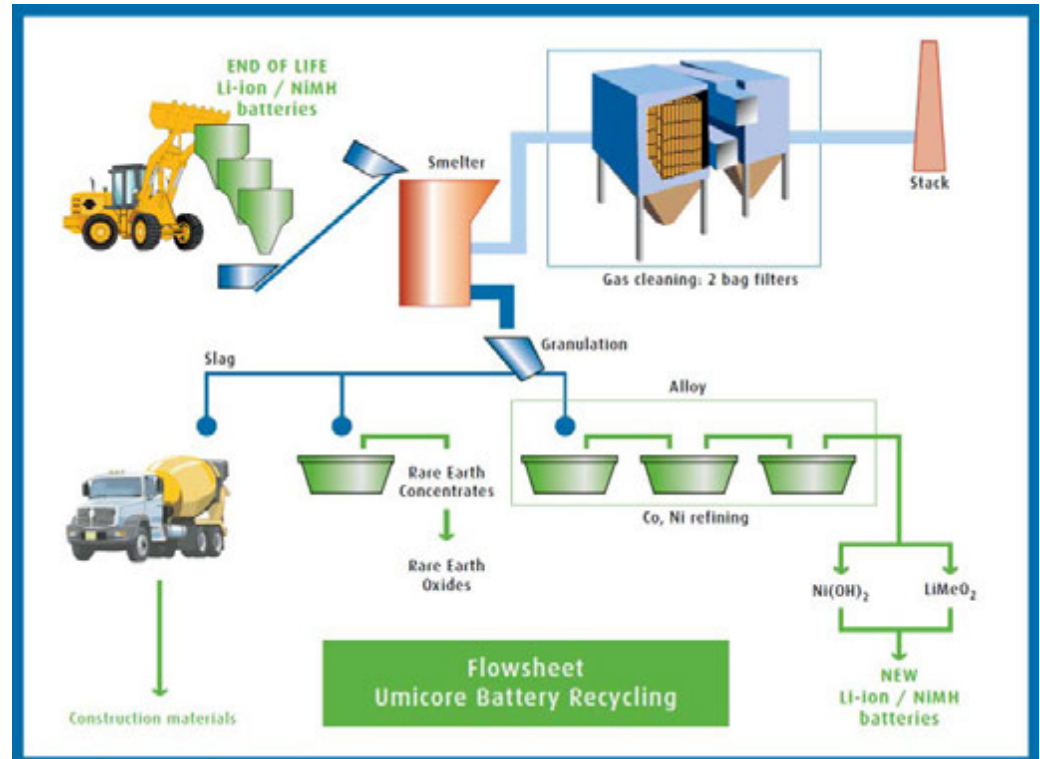


Recycling avoids the shaded steps and substitutes those on the following slides

# Pyrometallurgical Process:

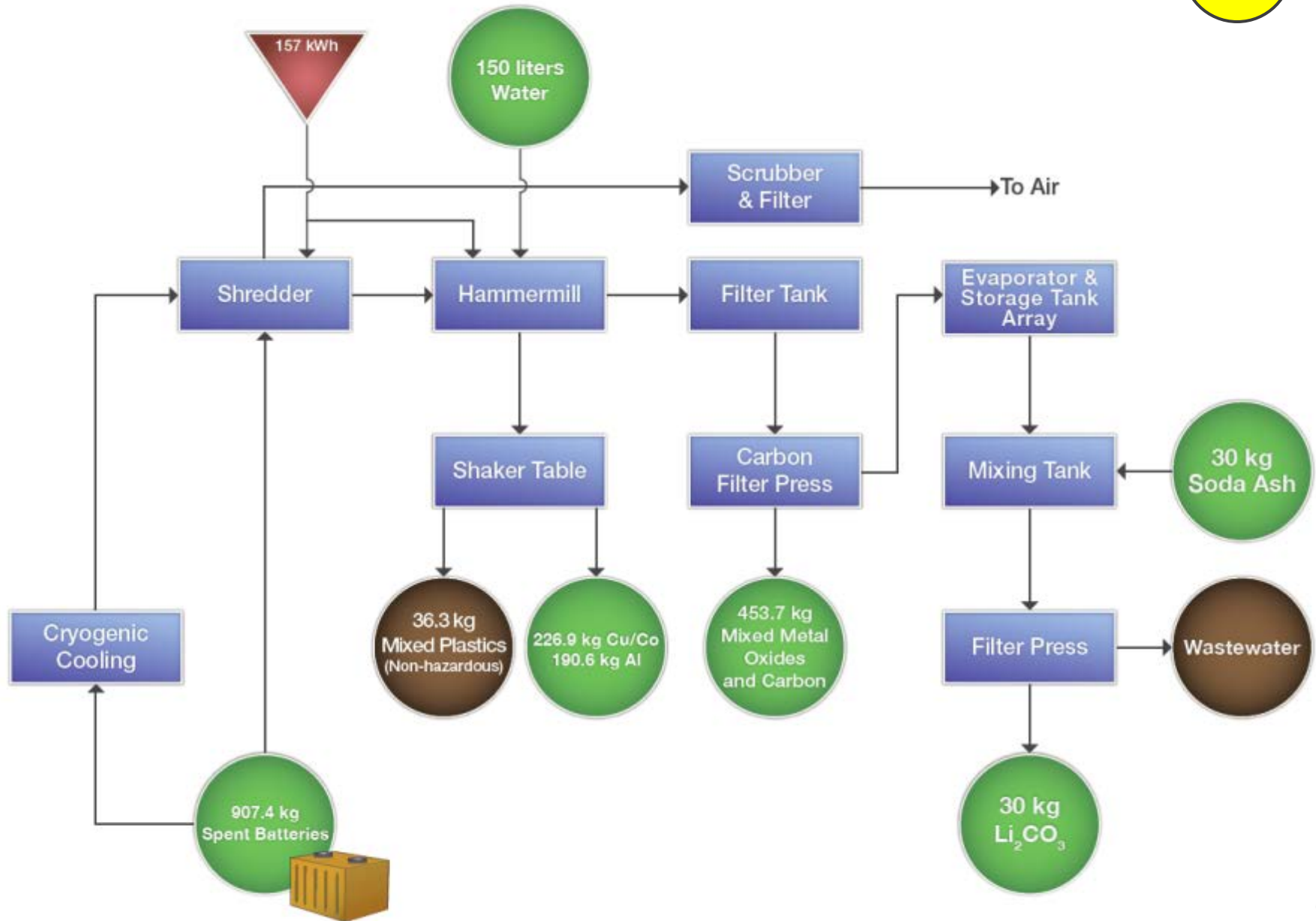
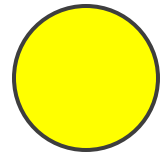
## Commercial smelting process recovers some metals

- These can take just about any input, high volume
- High-temperature required
  - Organics are burned for process energy
- Valuable metals (Co, Ni, Cu) recovered and sent to refining
  - Suitable for any use
  - 70% of cobalt production energy saved; sulfur emissions avoided
  - Fabrication still needed
  - **Less Co → less value**
- Off-gas treated at high-T
- **Li, Al go to slag**
  - Could be recovered
  - High \$ and E costs
  - Mn and Ti also to slag



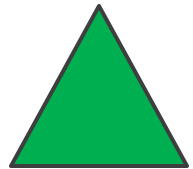
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# Intermediate physical recycling process recovers lithium carbonate and all metals

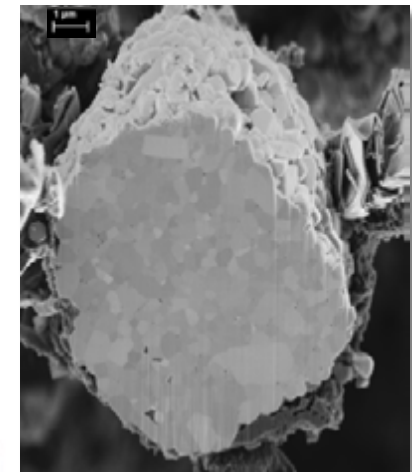
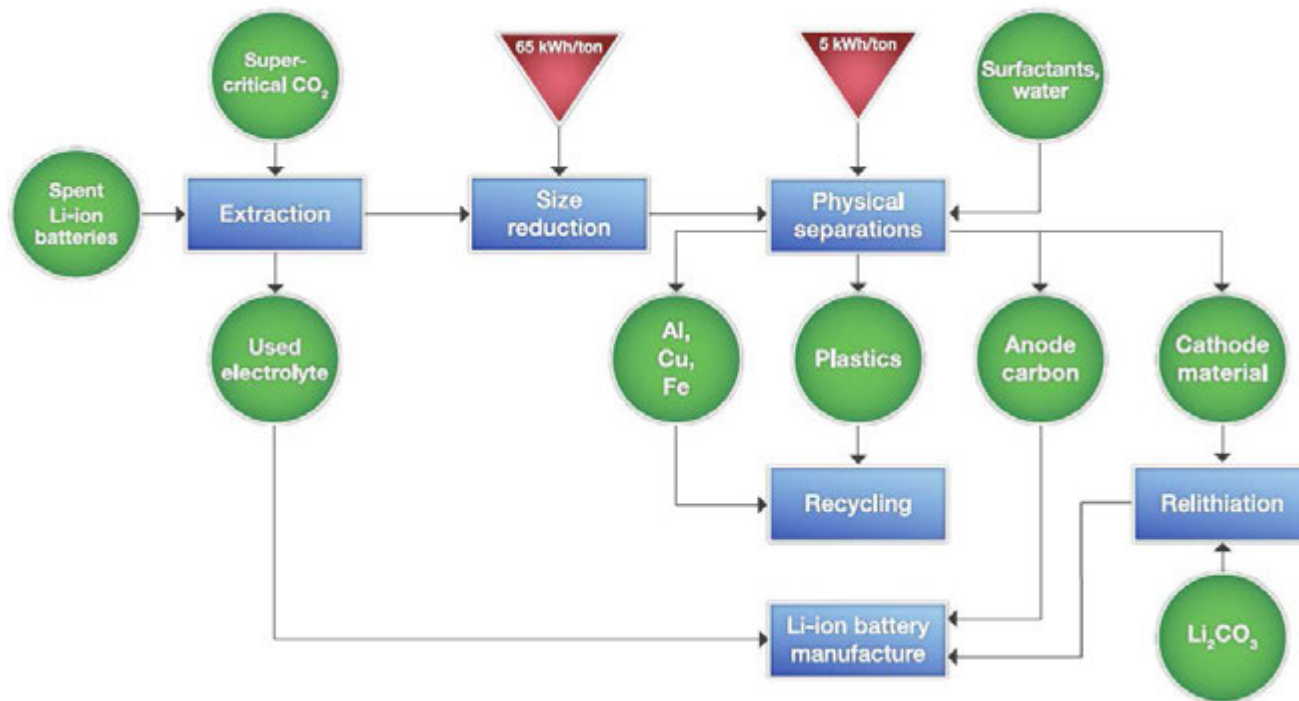




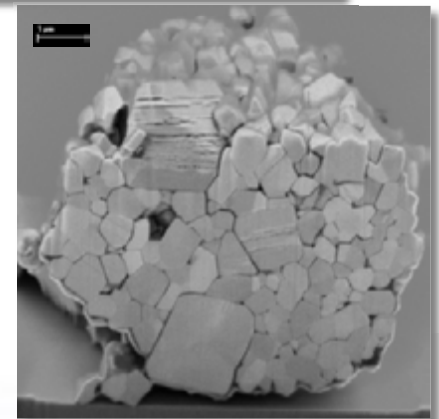
# Bench-scale direct physical recycling process recovers battery-grade materials



- Low-temperature process, low energy requirement
- Components are separated to retain valuable material structure
- Does not require large volume; could process prompt scrap
- Requires as uniform feed as possible
- Recovered cathode could be obsolete when finally recovered
- Quality must be assured



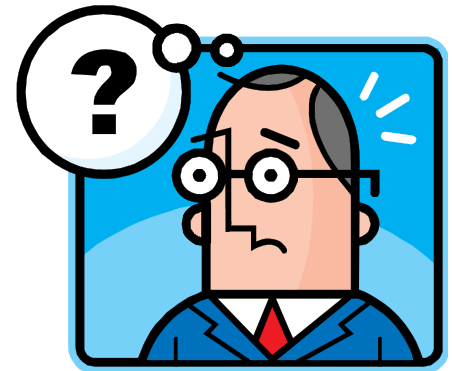
NCA as prepared  
←



6000 cycles  
←

# What if other cathodes are used instead of $\text{LiCoO}_2$ ?

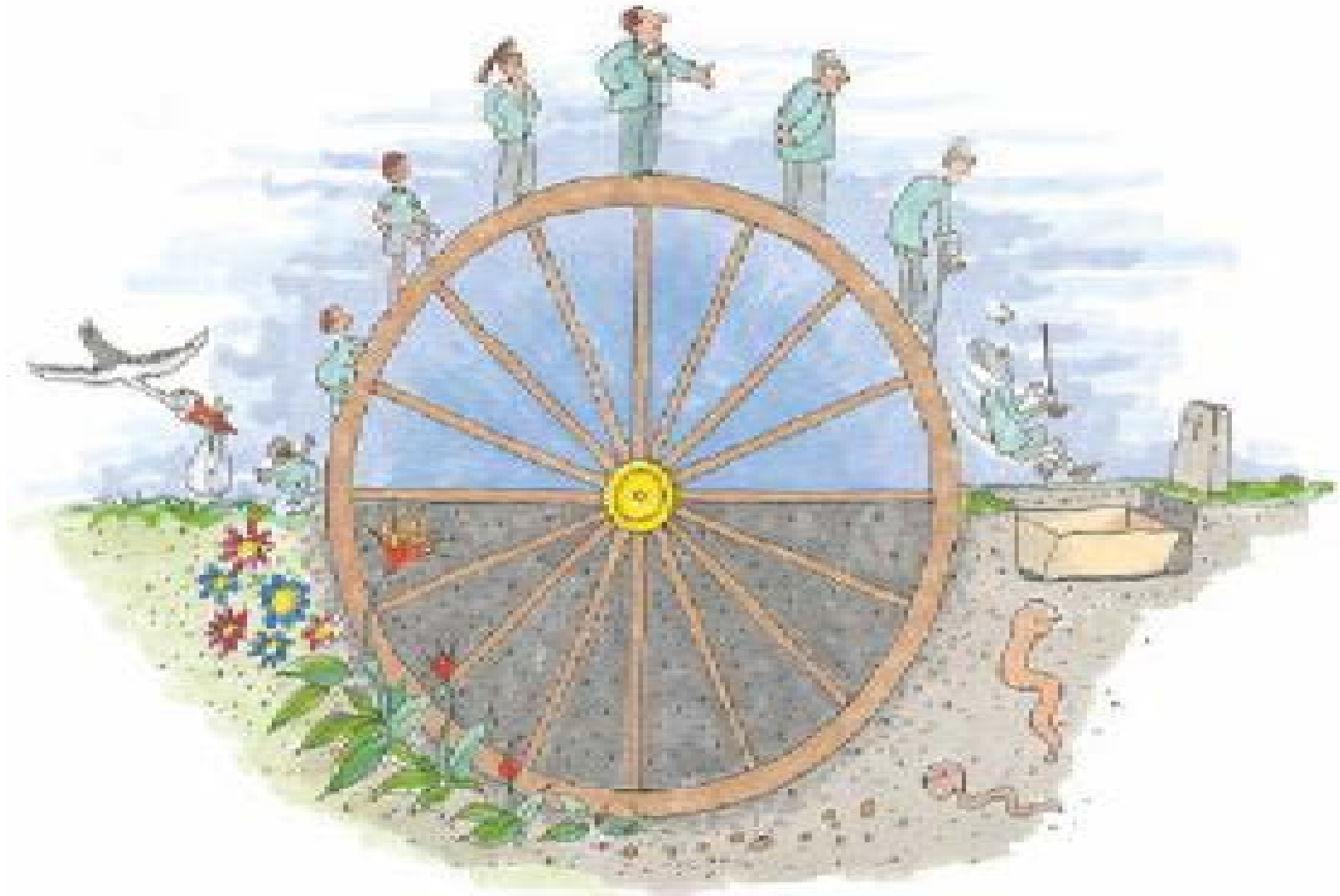
- **Value of recovered metals is reduced**
  - Cobalt recovery drives economics now
  - Some value remains in copper and nickel
- **Direct process could still recover high-value cathode material from clean stream**
- **Work is in progress to separate mixed cathode streams**
- **We haven't even begun to think about Li-S, Li-air or other developing chemistries yet.**

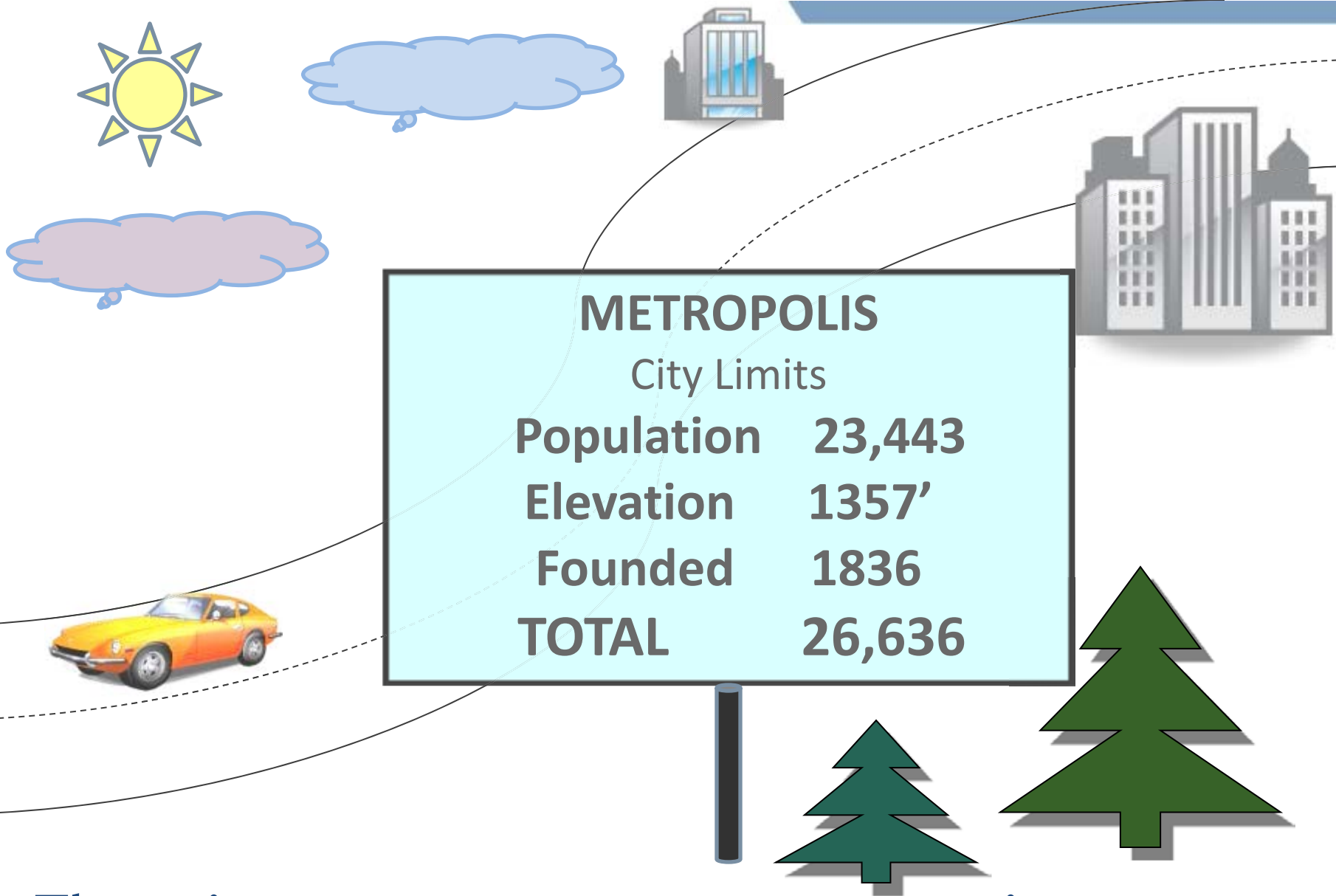




# Lifecycle analysis compares all process impacts

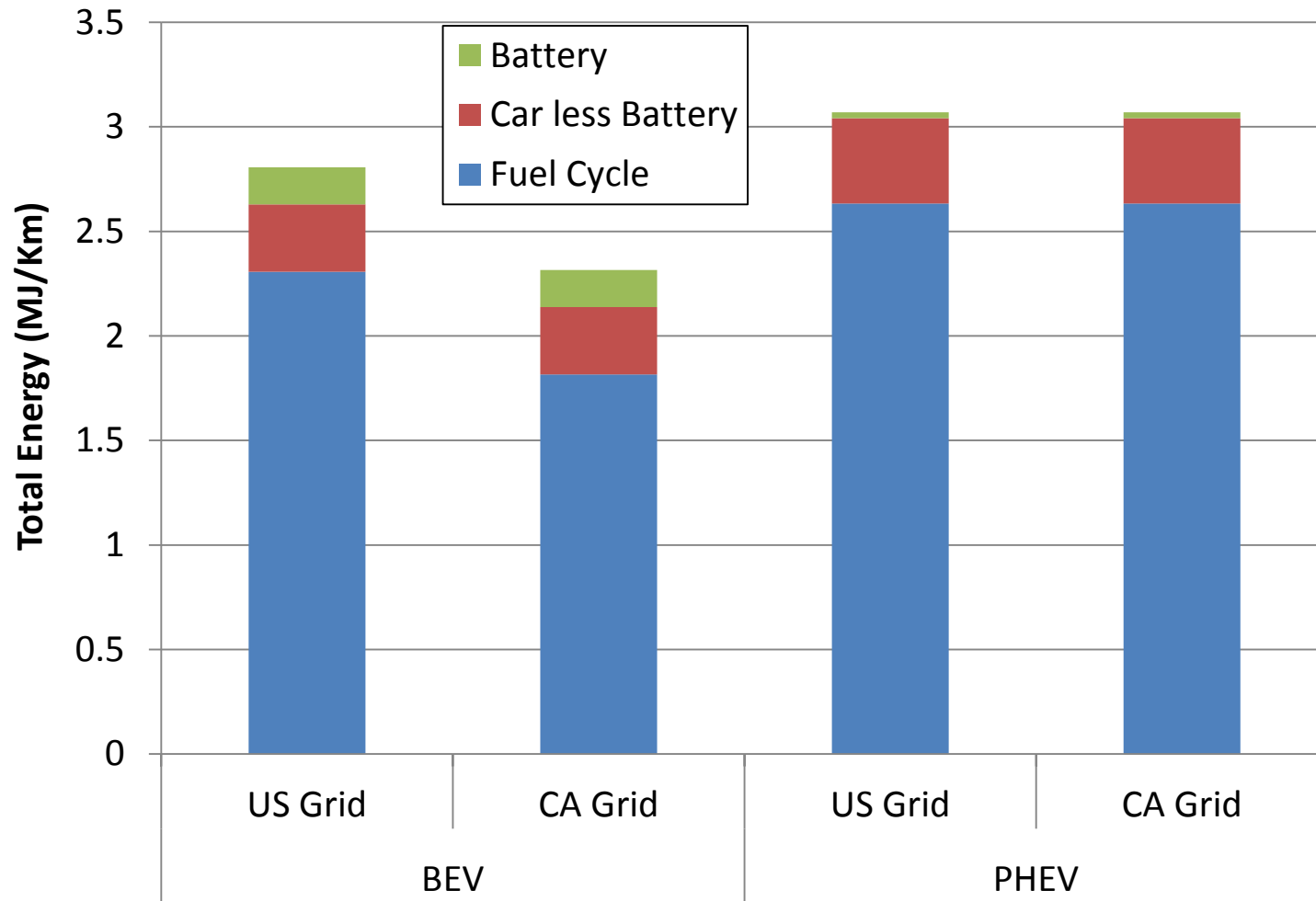
of a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal if any.



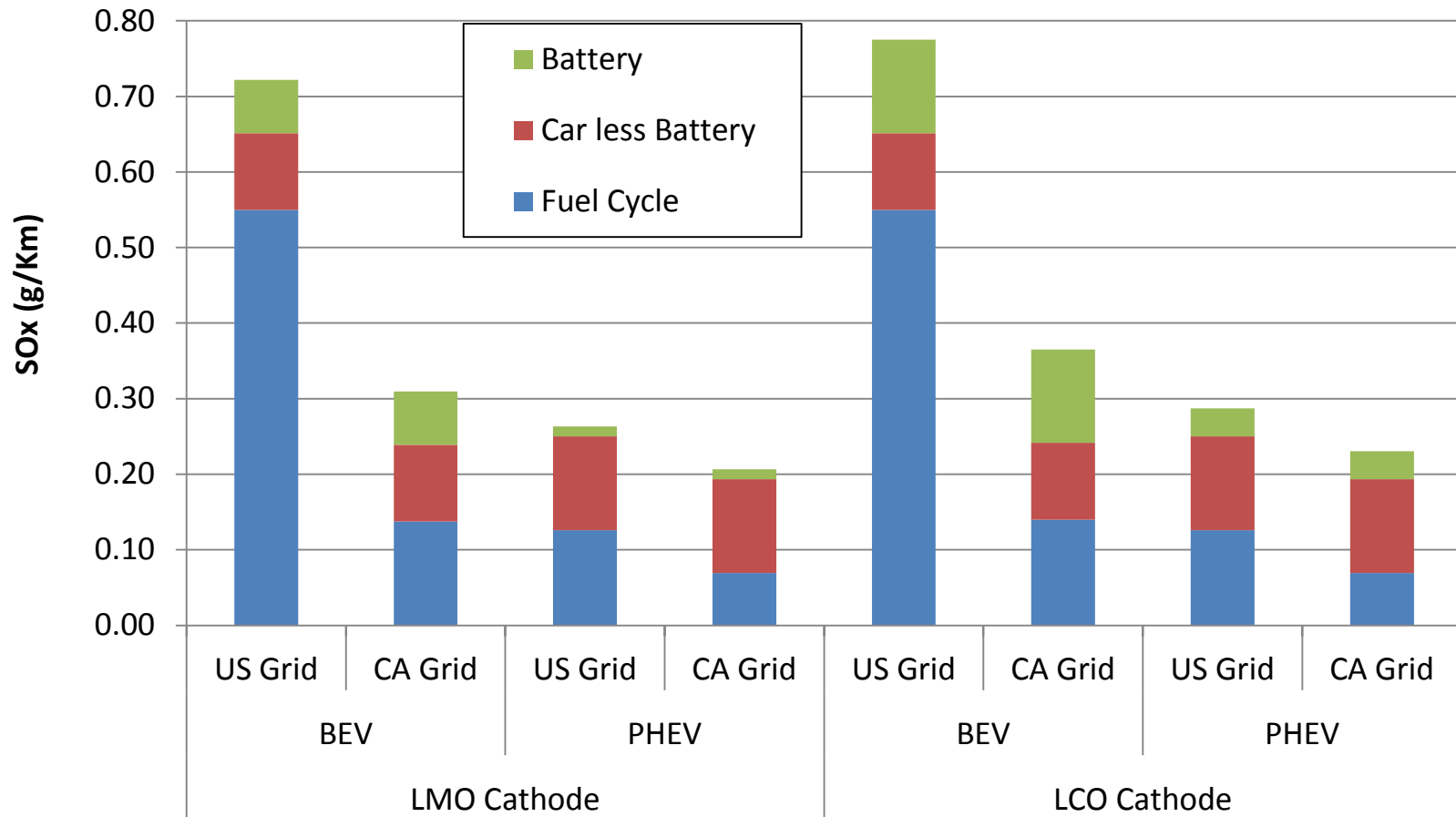


There is no correct way to aggregate impacts into a single “score.”

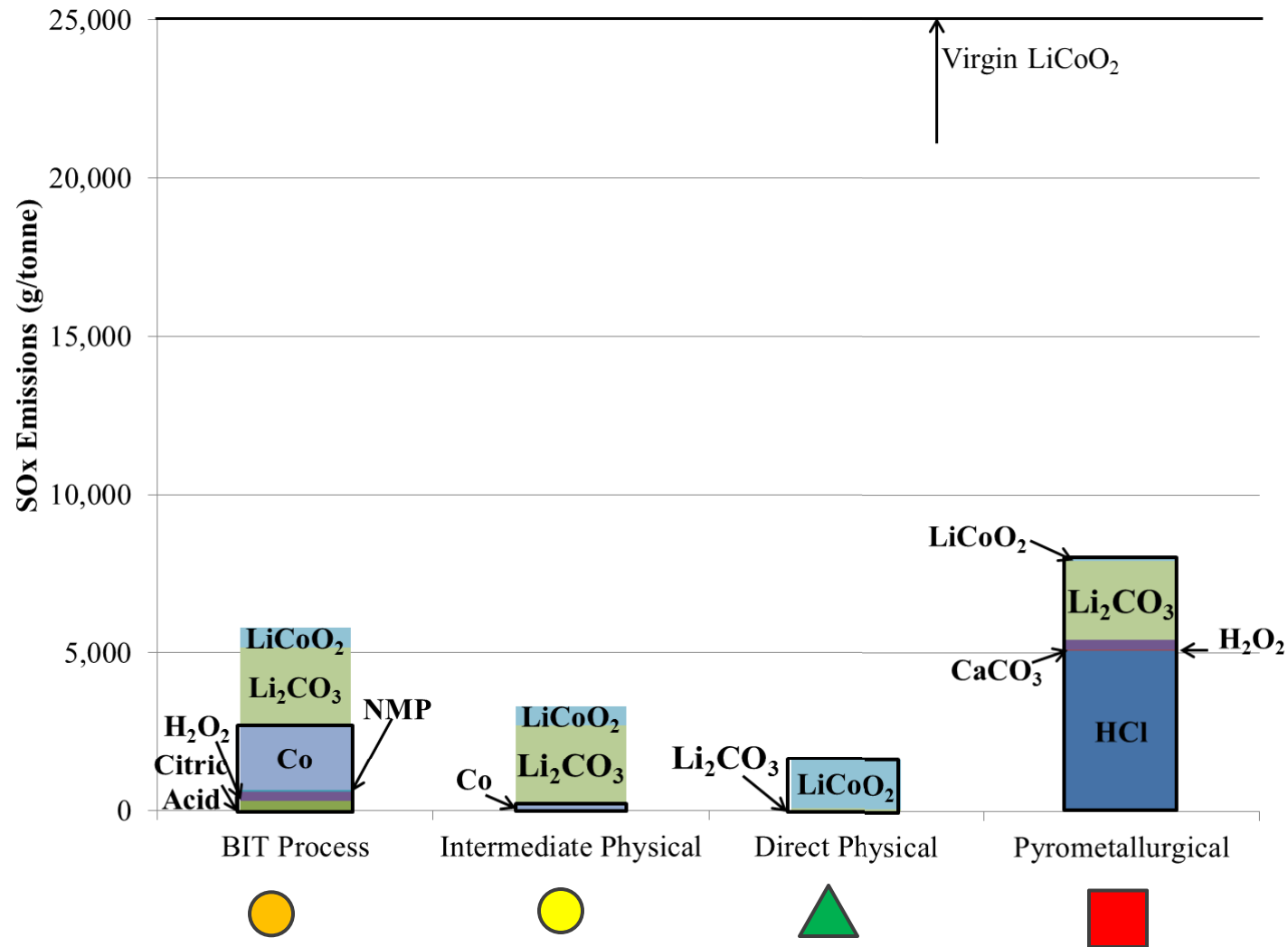
# Batteries are small contributors to life-cycle energy use and CO<sub>2</sub> emissions



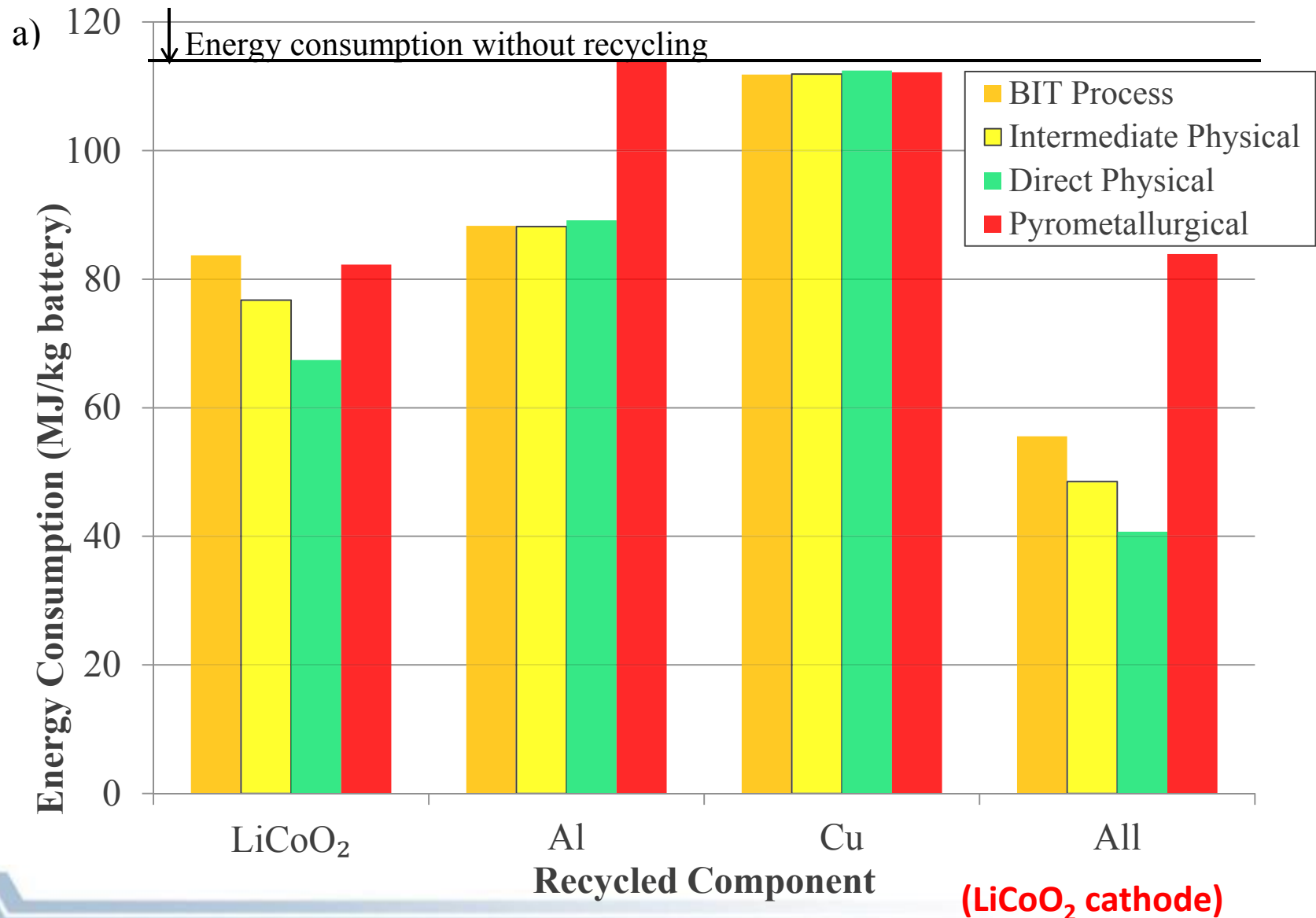
But make significant contributions  
to life-cycle  $\text{SO}_x$  emissions,  
especially if cathode contains cobalt or nickel



# Sulfur emissions are minimized if a cobalt- (or nickel-) based cathode is recycled



# Recovery of cathode and metals maximizes energy savings



# Recycling processes differ in important ways

	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni ,Cu in alloy	Metal salts, $\text{Li}_2\text{CO}_3$ or $\text{LiOH}$	Cathode, anode, electrolyte, metals
Feed requirements	None	Separation desirable	Single chemistry required
Comments	New chemistries yield reduced product value	New chemistries yield reduced product value	Recovers potentially high-value materials; Could implement on home scrap



# Cathode recovery could enable economical recycling

- **Value of constituents is low for LMO and LFP cathodes**
  - But cathode itself has high value
  - Heat available for smelter is reduced if titanate replaces carbon
  - Smelter cannot realize significant energy benefit of aluminum recovery
- **Direct process could recover high-value cathode material**
  - Mixed cathode materials could be separated before or after processing

Cathode	Price of Constituents (\$/lb)	Price of Cathode (\$/lb)
$\text{LiCoO}_2$	8.30	12–16
$\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$	4.90	10–13
$\text{LiMnO}_2$	1.70	4.50
$\text{LiFePO}_4$	0.70	9



# Rest-of-battery recycling will help economics

- **In Europe, 50% of cell materials must be recycled (as of 9/26/11)**
  - Collection is assumed
  - Goals have not yet been achieved
- **The rest of the battery is included in the EU 95% auto recycling requirement**
  - This may include enough valuable materials to make recycling the battery pay, even if  $\text{LiFePO}_4$  cathodes are used
- **The responsibility for EU recycling belongs to the company that makes the consumer product**



# How can we make it happen?

## Several strategies could facilitate recycling

### Ideal world:

- Standard configurations enable design of recycling equipment
- Standardization of chemistry reduces need for sorting and multiple processes

### Real world:

- Cell labeling will enable sorting
  - SAE working groups are developing chemistry identification and labeling
- Design for disassembly would enable material separation
- Favorable economics and regulations both needed
  - Europeans mandate recycling because it's right
  - US relies on finding economically-viable processes
    - *Must also be environmentally sound*
  - A combination of the two might work better



# Industry and government are working to enable battery recycling

- DOE funds battery recycling work
- SAE has several battery working groups
  - Recycling
  - Labeling
  - Transportation
- EPA performed a life-cycle assessment
- USABC and USCAR have a working group
- There are no US laws, only voluntary collection programs



# Thank you!

- Work sponsored by USDOE Office of Vehicle Technologies
- Contact me: [lgaines@anl.gov](mailto:lgaines@anl.gov)
- [http://www.transportation.anl.gov/technology\\_analysis/battery\\_recycling.html](http://www.transportation.anl.gov/technology_analysis/battery_recycling.html)

